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GASIFICATION/COMBINED-CYCLE SYSTEM FOR ELECTRIC POWER GENERATION

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16 ABSTRACT

This report describes a type of gasification/combined cycle system being considered for construction by a consortium of Louisiana cities that own electrical utility systems. The 115 MW system is expected to employ the Texaco Synthesis Gas Generation Process (TSGGP) to produce a fuel gas by partial oxidation of a hydrocarbon feedstock. The gas is cleaned to remove sulfur compounds, ash, and particulates, then burned as fuel for the gas turbine in a combined-cycle power system.

The commercially-proven TSGGP process accepts a large variety of hydrocarbons as feedstocks. The initial feedstock for this application is expected to be heavy petroleum residues, although the potential exists for utilization of coal and lignite. Other features of the proposed system include (1) high thermal efficiency (relative to conventional steam generators) resulting in part from efficient recovery of thermal energy from the gasification of feedstock; and (2) extremely low levels of pollutants (SOx, NOx) in emissions to the atmosphere.

The five participating municipalities have established a joint commission, "Louisiana Municipal Power Commission" (LAMPCO), which has retained the services of bond counsel and investment banking firms, and is proceeding with plans to implement the proposed power generation facility.

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GASIFICATION/COMBINED-CYCLE SYSTEM FOR ELECTRIC POWER GENERATION

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ABSTRACT

This report describes a type of gasification/combined cycle system being considered for construction by a consortium of Louisiana cities that own electrical utility systems. The 115 mw system is expected to employ the Texaco Synthesis Gas Generation Process (TSGGP) to produce a fuel gas by partial oxidation of a hydrocarbon feedstock. The gas is cleaned to remove sulfur compounds, ash, and particulates, then burned as fuel for the gas turbine in a combined-cycle power system.

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The five participating municipalities have established a joint commission, "Louisiana Municipal Power Commission" (LAMPCO), which has retained the services of bond counsel and investment banking firms and is proceeding with plans to implement the proposed power generation facility.

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SECTION I

INTRODUCTION

A group of Louisiana cities that own electric utility systems are forming a joint authority, under recently enacted State legislation, to build a 115-mw gasifier/combined-cycle generating plant and to arrange for the transmission of the electrical energy to the participating municipalities. The participants in this joint undertaking are the cities of Morgan City, Natchitoches, Opelousas, Thibodaux, and Franklin.[*,13] Present plans contemplate the distribution of electrical energy from the generation site to the participating municipalities via existing commercial transmission facilities. Airline distance between the two most widely-separated towns, Thibodaux and Natchitoches, is approximately 190 miles (see Exhibit 1). Current estimates place today's cost of the plant at about $50 million or $435 per kw of capacity, although this figure is sensitive to inflation factors.[17]

Because of apparent similarities between the proposed Louisiana plant and another low-emission gasification/cleanup/combustion system for use in electric power generation that has been the subject of EPA-sponsored research (the chemically active fluid bed (CAFB) process[15]), the Office of Energy, Minerals, and Industry of the U.S. Environmental Protection Agency asked the MITRE Corporation to prepare a description of the proposed Louisiana electric power generation system, with emphasis on the gasifier and gas clean-up portions of the overall system.

The following sections of this report present, first, an overview of the total system for producing electric power from carbonaceous or hydrocarbon fuels, and second, more detailed information on the operation and performance of certain of the major components in the gas production and cleanup portions of the system.

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*Superscripts denote information sources identified in the References (Section VI).

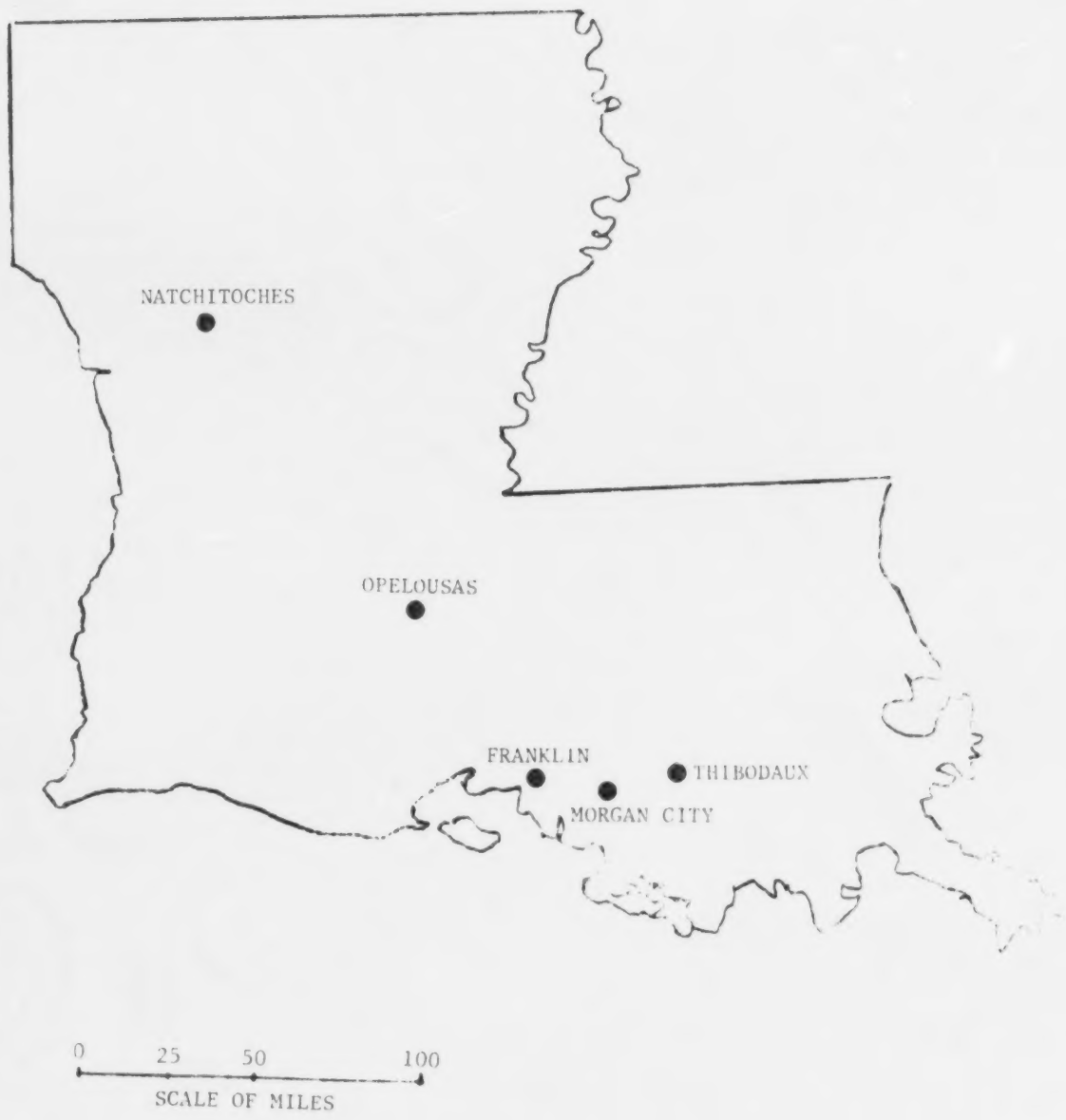


Exhibit 1. Location of participating Louisiana municipalities

SECTION II

SUMMARY

The gasification/combined-cycle system proposed to generate 115 mw electric power employs a gasifier that is widely used in industry -- the Texaco Synthesis Gas Generation System. The operational characteristics of gasifier are well established. The gasifier accepts a variety of low-grade petroleum residues or almost any "pumpable" hydrocarbon as feedstock, and forms a low-Btu fuel gas (100-150 Btu/ sfc) by partial oxidation. Sensible heat from the fuel is recovered in the form of high-pressure steam that is used to drive a steam turbine in the combined-cycle portion of the system. The cooled fuel gas is then cleansed of soot and particulate matter (by water wash) and sulfur compounds (by an absorption system) before being burned to drive the gas turbine of the combined cycle. Overall thermal efficiency of the system is estimated at about 38 to 40 percent.

Overall costs of the proposed system are estimated at about $50 million. For a hypothetical system of this size, about 37 percent is for the gasification and gas cleanup portions, 46 percent for the electric generations section, and 17 percent for offsite facilities (fuel storage, cooling towers, etc.).

The interface between the gasification/cleanup sections and the turbine combustor has been successfully demonstrated on a pilot-scale system. Tests indicate that NO_x emissions are lower than those produced by natural gas firing and CO emissions are about the same. The ability of a gasification/combined-cycle system to respond to fluctuations in electric power demand has been investigated by means of computer models which indicate that load changes can be successfully followed.

The joint commission of five municipalities in Louisiana is currently proceeding with plans to implement the 115 mw power generation facility.

SECTION III

CONCLUSIONS

- The proposed gasification/combined-cycle system is an innovative approach for meeting the specified electric power generation requirements. The technical and economic feasibility of the system has been investigated in detail by a series of studies that take into account environmental impacts of the system's operation.

- The proposed system provides potential for utilizing a variety of low-grade petroleum fractions and possibly coals as fuel feedstocks for meeting the specified power demands.

- The proposed system bears similarity to the chemically active fluid bed (CAFB) system being investigated by EPA in that it exhibits relatively high overall efficiency (compared with conventional systems), accepts a range of liquid hydrogen feedstocks, and is modular in size. However the proposed system differs from the CAFB in that it employs pressurized partial oxidation instead of atmospheric pressure and requires post-gasification removal of sulfur compounds instead of direct removal by solid sorbent during the combustion step.

- The proposed Lousiana facility has the potential for producing valuable data on operational parameters and pollutant emissions during start-up, load-change, and steady-state conditions.

SECTION IV

RECOMMENDATIONS

- MITRE recommends that EPA consider, in its planning, communication with organizations participating in the development of the Louisiana facility, with a view toward acquiring data from the testing and operation of the facility and its component processes and equipment.

- MITRE recommends that this action be taken immediately so that any special instrumentation needed for measurements of interest to EPA might be installed during construction of the facility rather than retrofitted.

SECTION V

OVERVIEW OF THE GASIFICATION/COMBINED-CYCLE SYSTEM

SYSTEM DESCRIPTION

The overall system converts heavy hydrocarbon fuels such as residual petroleum products, possibly with high sulfur content, into a clean, low-Btu gas that is used to fire a gas turbine in a combined-cycle electrical generation system. Heat from the gasification step is recovered in the form of steam, which is combined with steam generated from the gas turbine exhaust to drive the steam turbine of the combined-cycle system.

The more important interrelations within the overall system are shown by the simplified flow diagram in Exhibit 2. (This diagram, adapted from Figure 9 of Reference 7 and Figure 1 of Reference 9, is essentially similar to a block diagram for the proposed Louisiana facility as presented in an early report on this facility.[3])

Hydrocarbon fuel is pumped into a gasifier vessel (B)* where it is partially oxidized under elevated pressures (typically 10 to 40 atmospheres) and temperatures (1800 to 3000 F) to yield a low-Btu fuel gas mixture. The oxidant is atmospheric oxygen in the compressed air that is fed to the gasifier at a controlled rate to maintain an oxygen-to-fuel ratio of about half the value required for complete combustion. Under these conditions, the hydrocarbon is converted principally to carbon monoxide and hydrogen with some formation of carbon dioxide, steam, and carbon (soot). About 98 percent of the carbon content of the fuel is gasified in a single pass.

In the highly reducing environment of the gasifier, sulfur in the fuel reacts to form hydrogen sulfide (H_2S), carbonyl sulfide (COS), and carbon disulfide (CS_2). Nitrogen in the fuel reacts to form ammonia (NH_3) and molecular nitrogen (N_2). Conditions in the gasifier do not promote the formation of oxides of sulfur (SO_x) or of nitrogen (NO_x).

The fuel gas mixture that emerges from the gasifier contains soot and ash and may contain sulfur compounds; these materials must be removed before the mixture is suitable as a gas turbine fuel. Metals in the fuel feedstock are present in the ash as sulfides, suboxides, and possibly other forms. The ash is partially sequestered in the soot

*Letters in parentheses refer to items of equipment in Exhibit 2.

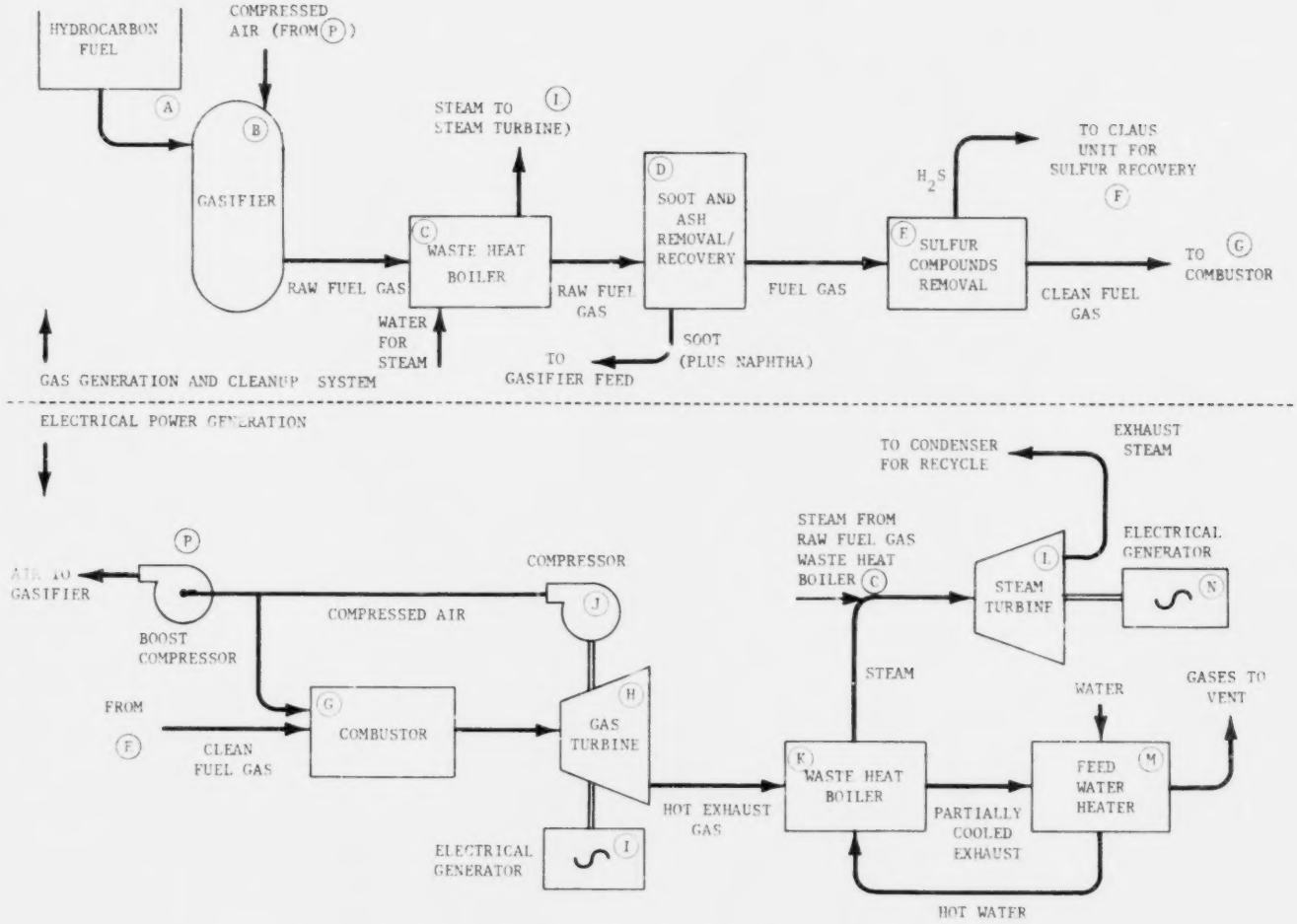


Exhibit 2. Air gasification with combined cycle (simplified diagram)

within the gas stream. After the fuel gas stream emerges from the waste heat boiler (C), it is water-scrubbed in a soot recovery system (D), which operates effectively on the high pressure gas to remove soot, ash, and any ammonia that was formed in the gasifier. The soot/water stream is then contacted with naphtha whereupon the soot is transferred to the naphtha phase. The (immiscible) naphtha phase and water phase are separated by decanting and the water is recycled for use in the gas scrubber. Soot is separated from the naphtha by flashing. Ash is removed from the soot by a process proprietary to Texaco Development Corporation, and is accumulated for disposal or for possible recovery of metallic values. (A flow chart of the soot recovery system is shown in Exhibit 4, page 13.)

The gas stream leaving the soot recovery system is cooled but still under high pressure. It is sent to a cleanup system for removal of sulfur compounds. Several candidate cleanup systems have been evaluated, but the final selection for use in the Louisiana power plant has not been made. Sulfur compounds (principally H_2S) separated from the gas stream are sent to a Claus unit where the sulfur is converted to the elemental form. The cleaned fuel gas stream is now ready for use in the combustor (G) and the gas turbine. It is emphasized that the fuel gas in this stream must be virtually free of particulate matter and H_2S because of possible damage to the gas turbine by these materials.

After adjustment of the temperature and pressure of the fuel gas stream, the gas enters a combustor unit (G) where it is burned with compressed air as the oxidant. The hot exhaust gases drive a gas turbine (H), which in turn drives an electric generator (I) and an air compressor (J), which supplies compressed air to the turbine. A portion of the compressed air is bled off and used as input to the gasifier. Because of the higher pressures in the gasifier, boost compression of the side stream is necessary (P).

Sensible heat is recovered from the turbine exhaust gases by a waste heat boiler (K), which generates high pressure steam that is used, in combination with steam produced by the gasifier/waste heat boiler (C), to drive a steam turbine (L) which, in turn, drives a second electrical generator (N). Partially cooled exhaust gases emerging from the low-temperature side of the waste heat boiler (K) are used to pre-heat feed water to the boiler. The cooled exhaust gases are then vented to the atmosphere. Exhaust steam from turbine (L) is condensed, used for cooling in the soot extraction system (D), and recycled for boiler feed.

TYPES OF FUELS

The gasification portion of the proposed Louisiana system employs the Texaco Synthesis Gas Generation Process (TSGGP) which will accept a variety of hydrocarbon feedstocks. Most liquid hydrocarbons that can be

pumped (including low-cost refinery residues that do not meet commercial fuel oil specifications) can be used as feedstock, since sulfur and metals content are not critical. There is a recommended limit on the salt level in the feedstock (not to exceed 10 pounds of salt per 1000 barrels) which may require desalting of some feedstocks prior to gasification. This is because sodium in the salt is generally deleterious to the refractory lining of the gasifier. The use of a great range of petroleum derived feedstocks has been amply demonstrated in TSGGP units around the world (See Appendix A).

During the first two years' operation of the proposed Louisiana facility, it is expected that the operating agency will have a base commitment for vacuum residuum fuels, with potential for later utilization of other fuel types.[4] The indicated flexibility of the TSGGP process in utilizing different fuels for the clean production of electric power can be of great advantage to the utility organization facing a choice of fuel sources. In addition, the potential for using coal in the form of oil or water slurry appears promising for this gasification system. A Texaco patent describes a gasifier designed to operate on a water slurry of petroleum coke.[8] A commercial gasifier that operated on coal was installed for use in ammonia synthesis at an Olin Mathieson plant in West Virginia over 17 years ago.[8] If this potential for utilizing coals as fuel is realized in commercial practice, it could offer great advantage to the operators of the proposed Louisiana facility by permitting the utilization of low cost lignite from deposits in the northern part of the State.

ENERGY AND EFFICIENCY RELATIONSHIPS

The overall plant efficiency for converting chemical energy of the fuel into electrical energy is estimated at 38 percent. This estimate is based on a detailed design analysis of a 294-megawatt plant employing today's off-the-shelf machinery and components. Substantial improvements in overall thermal efficiency are expected as allowable inlet temperatures for gas turbines can be increased.[9]

The key to the efficiency and the economics of the gasification/combined-cycle system is the efficient utilization of sensible heat. Typically, the gas produced by the gasifier contains about 70 percent of the gross heating value of the fuel as chemical energy, principally in the form of carbon monoxide and hydrogen, with a heating value of about 100 to 150 Btu per cubic foot (cold gas basis). Most of the remaining 30 percent is in the form of sensible heat of the product gas stream. Most of the sensible heat is recovered in the form of steam at about 1000 to 1500 psi by means of an appropriately designed heat exchanger (waste heat boiler). Burner efficiency in the turbine combustor is typically greater than 99 percent.

In the analysis of the 294 megawatt system alluded to above, just under half of the electrical energy output (145 mw) is produced by two gas turbines and just over half (149 mw) by a steam turbine.[7]

The difference in overall thermal efficiency of a system employing gasification instead of direct burning of fuel is a decrease of about 1.5 percent, which reflects minor losses of mass in the gas purification steps and some loss of low quality heat. This penalty is more than offset by the advantages offered by gasification, including flexibility in fuel supply, increased reliability, and decreased maintenance of turbines resulting from the use of ultraclean gas in the gas turbine combustor.[7]

CHARACTERISTICS OF FUEL GAS PRODUCED

Composition and heating values of typical fuel gases produced by the Texaco Synthesis Gas Generation Process and used as combustor fuel in a combustor test program conducted at Texaco's Montebello Research Laboratory are given in Exhibit 3.

The Texaco Synthesis Gas Generation Process has the capability of producing a range of gas compositions to meet different product requirements. (See Appendix A.) For the purpose of generating a clean fuel for a nearby combined cycle operation, there is no advantage to producing a medium-to-high energy content fuel rich in hydrogen or methane. In fact, there may be some disadvantage from the standpoint of energy penalty and increased NO_x formation in the turbine combustor. Compositions of gases produced under different conditions with different fuels are given in Appendix A.

POLLUTANTS IN WASTE DISCHARGES

The proposed gasification/combined-cycle system, while not totally pollution free, is expected to operate well within all applicable environmental standards. The system itself imposes strict requirements that the fuel gas be essentially free of particulates and acidic sulfur compounds before it is burned as turbine fuel. (The concentration of particles of various sizes expected to remain in the gas stream after cleanup was not determined in the present study.)

Nitrogen and Nitrogen Compounds

The strong reducing environment in the gasifier converts virtually all fixed nitrogen in the fuel to ammonia or free nitrogen. Measurements on the raw fuel gas from the gasifier reveal a nitric oxide (NO) content of only a few parts per billion, and other oxides of nitrogen in even lower concentrations. Ammonia produced in the gasifier is removed by the water wash in the soot extraction process. The potential exists for the formation of nitrogen oxides during combustion of the fuel in the

Exhibit 3. COMPOSITIONS AND HEATING VALUES OF GASES PRODUCED

RANGE OF LOW HEATING VALUE GASES PRODUCED AFTER GAS CLEANUP

	Case 1	Case 2	Case 3
H_2 Mol%	12.49	14.55	17.93
CO	18.70	22.14	21.89
CH_4	0.01	0.03	0.93
CO_2	2.78	---	0.07
N_2	65.21	62.48	58.42
A	0.81	0.80	0.76
HHV Btu/SCF	101	118	137
Kcal/Nm^3	950	1110	1287

RANGE OF MEDIUM HEATING VALUE GASES PRODUCED AFTER GAS CLEANUP

	Enriched Air	Oxygen and Low Methane Mode	Oxygen and Methane Rich Mode
H_2 Mol%	31.44	51.24	60.03
CO	36.39	47.51	21.94
CH_4	0.38	0.59	16.91
CO_2	---	---	---
N_2	31.33	0.14	0.23
A	0.46	0.52	0.89
HHV Btu/SCF	223	324	436
Kcal/Nm^3	2097	3048	4101

SOURCE: Reference 7

turbine combustor unit. However, because of the low-heating value of the fuel gas and the relatively low combustion temperatures, the rate of NO_x formation is significantly lower than with conventional fuels. Tests of NO_x emissions at Texaco's semi-works scale gasifier coupled with a combustor for a gas turbine indicated the concentration of NO_x in end-of-system emissions from the combustion of low heating value gas (110-150 Btu/cu. ft.) is about one-third of that produced by burning No. 2 fuel oil and one-half of that from natural gas.[7]

Soot and Unburned Fuel

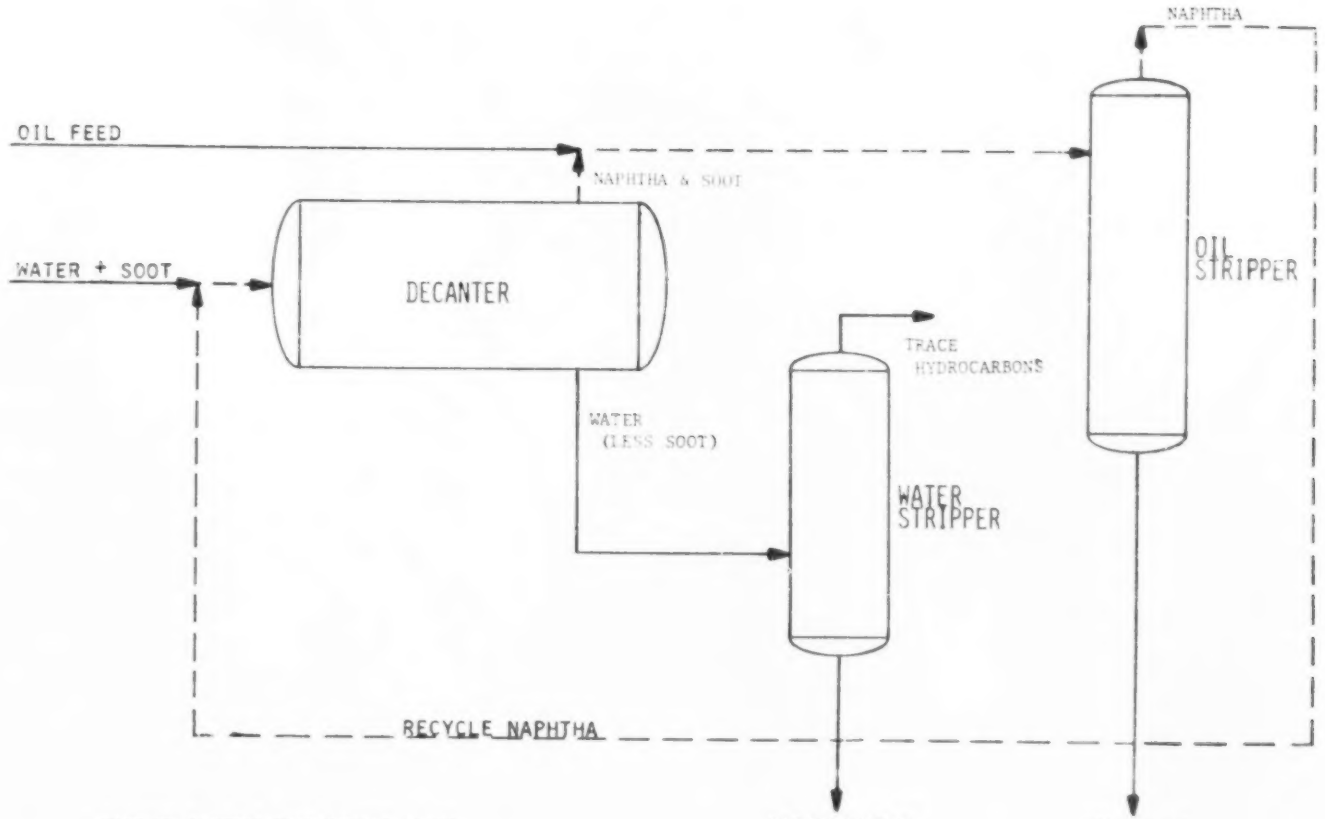
Particulate and amorphous carbon and other unburned fuel is removed from the gas stream by a water wash. It is separated from the water by additional processing steps (see Exhibit 4), and mixed with the feedstock supply to the gasifier. The solid carbon is thus "recycled to extinction".

Metals and Metallic Compounds

Metals in the feedstock are converted to sulfides, lower oxides, or the elemental state by the strong reducing conditions of the gasifier. These emerge in the gasifier output as ash, or under some conditions may form a slag in the gasifier. Under the present system concept and design, metals are removed with other ash components in the gas stream during the water-wash step of the soot removal system, and are separated from the soot by a proprietary process before the soot is recycled to the gasified feed.

Sulfur and Sulfur Compounds

Sulfur in the feedstock emerges from the gasifier in the form of H_2S, COS, and possibly CS_2. The greater part of these materials remain in the fuel gas stream as it goes through the waste heat boiler and soot removal system, and are removed thereafter by acid gas clean-up procedures. Several such procedures have been evaluated for this purpose, including those based on a physical absorption approach (such as the Rectisol or the Selexol process) and those based on chemical absorption (such as the Benfield or the Catacarb process). It is recognized that for the combined cycle operation, there would be some advantage to a process that operates at elevated temperatures so that the fuel gas would not have to be cooled to a low temperature before clean-up; also, to a process that removes the acidic sulfur compounds while leaving carbon dioxide in the gas stream, since expansion work could be realized from the carbon dioxide as it goes through the gas turbine.



SOURCE: Reference 7

Exhibit 4. Soot recovery and recycle system

When the acid gases are removed from the fuel gas, the hydrogen sulfide is sent to a Claus unit for recovery of the sulfide values as elemental sulfur with a conversion efficiency of about 99 percent. Most of the remaining sulfur is in the exhaust gas from the Claus unit in the form of SO_2, and can be removed by a conventional scrubber. The volume of exhaust gas from the Claus unit is miniscule in comparison with the exhaust from the gas turbine, hence it can be cleaned with much less expense and greater efficiency than could the entire throughput of the turbine.

INTEGRATION OF THE GASIFICATION AND COMBINED-CYCLE SUBSYSTEMS

In addition to the use of clean fuel from the gasifier to fire the turbine combustor, there are several points at which the gasification portion and the combined-cycle portion of the overall system depicted in Exhibit 2 are interrelated to enhance overall system efficiency. In particular:

-- Part of the air from the turbine compressor is bled off, boosted in pressure, and fed to the gasifier. Since most of the mass of air removed for use in the gasifier is returned to the turbine with the fuel gas, there is little if any change in net turbine mass flow using fuel gas from air gasification relative to the mass flow through the turbines if conventionally fueled. Hence existing turbines can use this fuel gas without aerodynamic modifications to the blading. Some changes are required in the flow control system.

-- Condensate from the steam turbine is used for cooling in the gas purification step and is recycled to the feedwater in the combined-cycle.

DEVELOPMENTAL STATUS OF THE GASIFIER/COMBINED-CYCLE SYSTEM

An experimental/developmental program was conducted in 1972-73 as a cooperative effort by Texaco, Inc., and two component organizations of United Aircraft Corporation (Turbo Power and Marine Systems, Inc., and Pratt and Whitney Aircraft) to assess the feasibility of using fuel gas from the TSGG gasifier in industrial gas turbines and to evaluate different combustion chambers and fuel injection arrangements over a range of operating parameters. Gas with heating value of 100 to 150 Btu per standard cubic foot was burned in one can (i.e., a 1/8 segment) of a PWA FT4 combustor.

Test results demonstrated that low Btu gas can be efficiently used in a gas turbine, that NO_x emissions will be lower than those produced by firing with natural gas, and CO emissions will be about the same as with

natural gas firing. The tests also indicate which modifications are required for the fuel introduction system, combustion chambers, and air bleed rates relative to those in a natural gas fired system.[9]

In addition to the large scale experimentation and demonstration by Texaco and others, a mathematical model of major portions of this type of system (the gasifier, gas cleanup, gas turbine/generator and booster compressor) has been developed by C.F. Braun & Co. for dynamic simulation studies. Since gasification processes normally operate at a steady state over long periods and gas turbine/generators can experience rapid fluctuations in load and require varying fuel demands, the question arises of the ability of the gasification section of the system to respond to changing fuel flow requirements when there is no intermediate fuel storage. The C.F. Braun model facilitates investigation of the dynamic response of various system components under conditions of changing load. The simulation study indicates that "... the combined plant is a stable system and that the fuels plant can follow load fluctuations in the power generating system without upsets. It shows further than the system can be automated by conventional control equipment to operate with a minimum of manual supervision."[1]

In the latter half of 1974, Beard Engineering, Inc., of Baton Rouge published reports of two studies that indicate the feasibility of using a gasifier/combined-cycle system to power electrical generating facilities in Louisiana (References 2 and 3). On the basis of these and subsequent studies, plans have been developed for building a gasification/combined-cycle electric power plant to serve five municipalities in Louisiana. Enabling legislation has been enacted by the State Legislature which permits local governments to enter jointly into such an enterprise. The five municipalities identified in Section I established, in October 1975, a joint commission names "Louisiana Municipal Power Commission" (LAMPCO). This commission has retained the services of bond counsel and investment banking firms, and is proceeding with plans to implement the proposed 115 mw central power facility on which a study is now being completed.[4]

System Cost

According to a 1973 cost estimation procedure prepared by Texaco, Inc., the cost of a 294 mw plant is estimated at $70.5 million, or about $240 per kw capacity (Appendix B). At this rate, the 115 mw Louisiana facility would cost about $28 million. Capital costs are, of course, highly sensitive to inflation. Current estimates place the cost at about $50 million, although it is recognized that additional inflationary effects can occur before bids are received.[17]

The gasification and gas cleanup portions of a hypothetical 150 mw system are estimated to account for 37 percent of the overall investment, the electric generation section about 46 percent, and the offsite facilities (fuel storage, cooling water distribution, cooling towers, etc.) for about 17 percent of the overall system capital costs.[20] In the proposed Louisiana facility, the sulfur removal portion of the system is estimated to account for about five to six percent of the overall system costs.[4]

The present study revealed no up-to-date estimates for the cost of electrical energy from a gasification/combined-cycle system. Texaco's cost estimation procedure (reproduced in Appendix B) is based on 1973 costs of equipment, labor, and fuel; hence its estimated cost of electricity produced (given in Appendix B) is not applicable to current conditions. The procedure could be used with updated inputs to yield new estimates of product electricity costs that more nearly reflect current conditions. The procedure can also be used for estimating equipment, labor, fuel, etc. It is noted that the value assigned to the feedstock accounts for a large part of the cost of producing clean fuel gas. For example, residual oil at a cost of $8 per barrel represents about 80 percent of the cost of clean fuel gas produced using air as the oxidant.[7] Relations between the cost of producing fuel gas and the cost of residuum feedstock are given in Exhibit 15 of Appendix B.

COMPARISON WITH CAFB PROCESS

The TSGGP process has certain points of similarity with the CAFB process of ESSO Ltd., being investigated by EPA. Both can be used with a variety of low grade petroleum fractions to generate fuel gas for electric power generation while releasing relatively low quantities of atmospheric pollutants. Both exhibit relatively high overall thermal efficiency, and both are essentially modular in size, in that there is an effective upper limit to the capacity of existing units. Multiple units can be combined to obtain large plant capacity for steam or electrical energy generation without loss in efficiency.

There are, however, several dissimilarities between the TSGGP and the CAFB approaches. Principal among these are the pressurized partial combustion in the gasification/combined-cycle system employing the TSGGP, with its requirement for scrubbing of H_2S and its production of ultra-clean fuel gas to fire a gas turbine. The CAFB process, on the other hand, employs atmospheric partial combustion with direct removal of sulfur components by fluidized solid sorbent. The CAFB approach has potential for retrofit to existing steam-to-electric generators. When used in a retrofit mode, the CAFB could not be expected to attain as high a thermal efficiency as the gasifier/combined-cycle system.

POTENTIAL OPPORTUNITIES FOR ENVIRONMENTAL R&D; RECOMMENDATIONS

The proposed Louisiana facility has the potential for producing valuable data on the operational parameters and pollutant emissions during steady-state operation as well as startup and load change conditions. Such information would be useful not only to indicate the efficiency and cleanliness of operation of this overall facility and its component processes, but to permit comparison of this system with others that serve similar markets, such as the CAFB process.

The design engineer has indicated that operational data would routinely be recorded during the operation of the facility and that test data would be developed. He expressed the opinion that such data would be available to EPA and other organizations having legitimate interests in the facility's operations.[4] A member of the management of the Texaco Development Corporation also has indicated that, under proper circumstances, the Corporation might be receptive to EPA's request that EPA representatives be allowed to visit the gasification facility at Texaco's Montebello Research Laboratory.[22]

In view of EPA's interest in demonstrating new methods for utilizing fossil fuels in an environmentally acceptable manner, its involvement in R&D of processes for accomplishing this aim, and the above-cited expressions of cooperation by organizations involved in the proposed full-scale Louisiana plant, MITRE strongly recommends that EPA consider in its planning the initiation of communications with organizations participating in the development of the Louisiana facility in an effort to acquire data from the testing and operation of this facility and its component processes and equipment. MITRE further recommends that this action be undertaken immediately in order that any special instrumentation needed for measurements of interest to EPA, but not routinely taken by the owners/operators of the facility, might be installed during the construction of the plant rather than retrofitted after construction is completed.

SECTION VI

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SECTION VII

APPENDICES

APPENDIX A. THE TEXACO SYNTHESIS GAS GENERATION PROCESS

A-1. Current Uses of the Texaco Process

The Texaco Synthesis Gas Generation Process (TSGGP) is a widely used, well established process for converting hydrocarbon feedstocks to a variety of gaseous products, principally high purity hydrogen for ammonia production and synthesis gas (mixtures of carbon monoxide and hydrogen) for use in the manufacture of chemicals. Currently, the TSGGP is used in over 60 commercial plants around the world. Exhibit 5 is a partial listing of companies that use the process, their locations, and the feedstock used. Single commercially-proven TSGGP units can produce up to 110 million SCFD of hydrogen plus carbon monoxide. Exhibit 6 shows the final product as well as feedstock of 16 recent installations. Exhibit 7 summarizes capacity, feedstock, and product information for plants in which heavy oils are used as feedstock. Such oils are planned to be used as feedstock in the initial operation of the proposed Louisiana plant.

A-2 Operational Considerations; Variety of Products

In the TSGGP process, the partial oxidation reaction takes place within a refractory-lined pressure vessel. It is basically a non-catalytic flame-type reaction involving the incomplete oxidation of a hydrocarbon feedstock with air, oxygen-enriched air, or oxygen introduced in less-than-stoichiometric quantities. An excessive ratio of oxidant to hydrocarbon will cause an undesired degree of complete oxidation, producing carbon dioxide and water. To keep the production of soot at acceptably low levels when oxygen or enriched air is used as the oxidant, it is necessary to operate at oxygen rates that yield reaction temperatures higher than can be handled by commercially available refractories. Hence when these oxidants are used, steam is added to the reaction as a temperature moderator. The steam may also serve as a source of hydrogen when a high-hydrogen-content product is desired. When air is the oxidant, the nitrogen content serves as the temperature moderator.

Exhibit 5. SYNTHESIS GAS GENERATION PROCESS PLANT OWNERS AND LOCATIONS*

OWNER	PLANT LOCATION	RAW MATERIAL
ANIC S.p.A.	Gela, Sicily	Natural Gas
ANIC S.p.A.	Ravenna, Italy	Natural Gas
Asahi Chemical Industry Co.,Ltd.	Nobeoka, Japan	Crude Oil
Badische Anilin & Soda Fabrik A.G.	Ludwigshafen/Rhein, Germany	Heavy Fuel Oil
BASF (Plant II)	Ludwigshafen/Rhein, Germany	Heavy Fuel Oil
Borden International (Alba, S.A.)	Cubatao, Brazil	Heavy Fuel Oil
Brockville Chemicals. Ltd.	Maitland, Ontario	Natural Gas
Compania Insular del Nitrogeno,S.A.	Las Palmas, Canary Islands	Heavy Fuel Oil, Naphtha
Courrieres-Kuhlmann	Harnes, France	By-product Gas
C.S.R. Chemicals Ltd.	Sydney, Australia	Heavy Fuel Oil
E. I. duPont de Nemours & Co.,Inc.	Huron, Ohio	Natural Gas
The Fertilizers & Chemicals Travancore Ltd. (Stage II)	Alwaye, Kerala State, South India	Naphtha
The Fertilizers & Chemicals Travancore Ltd. (Stage III)	Alwaye, Kerala State, South India	Naphtha, Heavy Fuel Oil
W. R. Grace & Company (Nitrogen Products Div.)	Woodstock, Tennessee	Natural Gas
Hemijska Industrija Pancevo (Invest-Import representing Fabrika Azotnih Djubriva - HIP)	Pancevo, Yugoslavia	Natural Gas or Heavy Fuel Oil

*As of 4/1/70

SOURCE: Reference 22

Page 1 of 3

Exhibit 5. (Continued)

OWNER	PLANT LOCATION	RAW MATERIAL
Imperial Chemical Industries, Ltd.	Billingham, England	Heavy Fuel Oil, Naphtha
Imperial Oil Co. (Esso)	Dartmouth, N.S.	LPG
Kaohsiung Ammonium Sulfate Corp., Ltd.	Kaohsiung, Taiwan	Heavy Fuel Oil
Government of the Republic of Korea	Chung-Ju, Korea	Navy Special Fuel Oil
Etablissements Kuhlmann	La Madeleine Les Lille, France	Naphtha
Nippon Steel Corporation	Hirohata, Japan	Heavy Fuel Oil
Nitratos de Castilla, S.A.	Valladolid, Spain	Heavy Fuel Oil, Naphtha
Nitto Chemical Industry Co., Ltd.	Hachinohe, Aomori, Japan	Crude Oil
Nitto Chemical Industry Co., Ltd.	Yokohama, Japan	Crude Oil
NV Nederlandse Staatsmijnen	Geleen, Netherlands	Natural Gas
Petroleo Brasileiro, S.A.	Cubatao, Brazil	Refinery Gas
Phosphoric Fertilizers Industry	Kavala, Greece	Crude Oil
Sociedade Portuguesa de Petroquimica, S.A.R.L.	Lisbon, Portugal	Naphtha
Manifattura Ceramica Pozzi,S.p.A.	Ferrandina, Italy	Acetylene Tail Gas, Natural Gas
Resins Inc.	Cayagande, Oro, P.I.	Heavy Fuel Oil
Rohm and Haas Company	Deer Park, Texas	Natural Gas, Acetylene Tail Gas

Exhibit 5. (Continued)

OWNER	PLANT LOCATION	RAW MATERIAL
Seitetsu Kagaku Company, Ltd. (Formerly Befu Chemical Co., Ltd.)	Hyogo-Pref., Japan	Crude Oil
Showa Denko K.K. - Plant 1	Kawasaki-shi, Kanagawa-ken, Japan	Refinery Gas, Crude Oil
Showa Denko K.K. - Plant 2	Kawasaki-shi, Kanagawa-ken, Japan	Crude Oil, Refinery Gas
Aktiebolaget Svenska Salpeterverken - Plant I	Kvarntorp, Sweden	Heavy Fuel Oil, Shale Oil
Aktiebolaget Svenska Salpeterverker - Plant II	Kvarntorp, Sweden	Heavy Fuel Oil
Standard Oil Co. of California	El Segundo, Calif.	Vacuum Resid
Taiwan Fertilizer Corporation, Factory No. 7	Hualien, Taiwan	Heavy Fuel Oil
Texaco Inc.	Los Angeles, Calif.	Heavy Fuel Oil or Vacuum Residuum
Tokuyama Soda Company, Ltd.	Yamaguchi-Pref. Japan	Crude Oil
Toyo Soda Manufacturing Co.,Ltd.	Yamaguchi-ken, Japan	Crude Oil
Toyo Koatsu Industries, Inc.	Omuta, Japan	Crude Oil
Ube Industries, Ltd. - Plant 1	Ube, Yamaguchi-Pref., Japan	Crude Oil
Ube Industries, Ltd. - Plant 2	Ube, Yamaguchi-Pref., Japan	Crude Oil

Exhibit 6. RECENT TEXACO SYNTHESIS GAS GENERATION PLANTS: LOCATION, FEEDSTOCK, AND FINAL PRODUCT

LOCATION	STARTUP DATE	FEEDSTOCK	FINAL PRODUCT
Italy	1965	Gas	Methanol
Puerto Rico	1965	Naphtha/LPG	Oxo Products
Nova Scotia	1965	Naphtha/LPG	Iron
Spain	1965	Heavy Fuel Oil/Naphtha	Ammonia
India	1966	Heavy Fuel Oil/Naphtha	Ammonia
Greece	1966	Crude Oil	Ammonia
Germany	1966	Heavy Fuel Oil/Crude Oil	Ammonia
Formosa	1966	Heavy Fuel Oil	Ammonia
Germany	1967	Heavy Fuel Oil	Oxo Products
U.S.	1967	Vacuum Residuum	Hydrogen
Netherlands	1968	Gas	Ammonia
Japan	1969	Heavy Fuel Oil	Iron
U.S.	1970	Vacuum Residuum	Hydrogen
Australia	1971	Heavy Fuel Oil/Naphtha	Oxo Products
Germany	1974	Heavy Fuel Oil/Naphtha	Oxo Products, Methanol, Hydrogen, Carbon Monoxide
Philippines	3rd Quarter 1974	Heavy Fuel Oil	Methanol

SOURCE: Reference 2.

Exhibit 7. TEXACO SYNTHESIS GAS GENERATION PLANTS
USING HEAVY OILS AS FEEDSTOCK

Country	No. of Plants	Total Capac. MMSCFD H2+CO	Feedstocks	Final Products
U.S.A.	4	130.3	Hvy. Fuel Oil, Crude Oil, Vac. Bottoms	Ammonia Refg. Hydrogen
Japan	11	132.9	Hvy. Fuel Oil, Crude Oil	Ammonia, Reducing Gas
Spain	3	46.4	Hvy. Fuel Oil	Ammonia
Germany	2	51.9	Hvy. Fuel Oil, Crude Oil	Ammonia, Oxo
Taiwan	2	10.3	Hvy. Fuel Oil	Ammonia
France, Canada, Brazil, Belgium, England, Italy, Korea, Sweden, Denmark, Yugoslavia, India, Greece, Australia	1 each	183.2	Hvy. Fuel Oil, Crude Oil	Ammonia, Methanol, Oxo
Totals	35	555.0		

SOURCE: Reference 2

The gasifier equipment has proven highly reliable in long-term operation. Commercial experience reveals that refractory lining last three to five years and burners in the gasifier have lives of several years. Pilot units indicate no burner problems at high pressures or with highly viscous feedstock.[7]

The gasifier can be operated at 10 percent of design capacity; turndown to 50 percent or less of normal system capacity is practiced in commercial units.

The partial oxidation products of a pure hydrocarbon may include carbon monoxide, hydrogen, methane, carbon dioxide, and carbon (as soot) (see Exhibit 8 for reactions) in addition to nitrogen and trace quantities of nitrogen oxides if air is the oxidant. Metals, other ash components, and sulfur compounds in the fuel may enter into side reactions to yield byproduct materials as discussed in Section V of this report. The composition of the product gas can be varied by controlling the oxidation rate and other reaction conditions to favor a high methane content, high hydrogen content, etc., depending on the intended use of the product gas, e.g., as fuel, as a source of pure hydrogen, or as a synthesis gas for subsequent chemical processing. Considering the product gases as a fuel, their heating value is typically in the range of 100-150 Btu/SFC if air is the oxidant, or around 300 Btu/SFC is oxygen is the oxidant. (See Exhibit 3.)

A-3 Coal as Feedstock

The lists of current applications of the TSGGP in Exhibits 5 through 7 indicates that all of these units use gases or l[illegible] petroleum derivatives as feedstocks. Extensive experimentation on use of coal slurries and petroleum coke feedstocks has been conducted at Texaco's pilot and semi-works experimental facilities. Exhibit 9 shows ultimate analyses and heating values of some of the solid materials that have been gasified continuously. Exhibit 10 shows the compositions of the gaseous products.[25] Some 90 to 98 percent of the feedstock carbon is gasified in single pass, with potential for recycling carbon extracted from the gas stream by the soot recovery system. A commercial unit which apparently used an earlier version of the TGSSP process, was constructed more than 17 years ago for use at an Olin Mathieson plant in West Virginia to produce synthesis gas from coal, for use in ammonia manufacture.[8]

APPENDIX B. SYSTEM COST ESTIMATION

Reproduced below are excerpts from a Texaco brochure which show cost elements and relationships that can be used to estimate the operating costs of a gasification/combined-cycle system and cost of products.

Exhibit 8. CHEMICAL REACTIONS IN THE PARTIAL OXIDATION OF A HYDROCARBON

OXIDATION	$(CH_2)_N + N/2\ O_2 \longrightarrow N\ H_2 + N\ CO$
STEAM CRACKING	$2(CH_2)_N + N\ H_2O \longrightarrow N\ CH_4 + N\ H_2 + N\ CO$
HYDROCRACKING	$(CH_2)_N + N\ H_2 \longrightarrow N\ CH_4$
STEAM REFORMING	$H_2O + CH_4 \longrightarrow 3\ H_2 + CO$
WATER GAS SHIFT	$H_2O + CO \longrightarrow H_2 + CO_2$
CARBON FORMATION	$(CH_2)_N \longrightarrow N/2\ CH_4 + N/2\ C$

SOURCE: Reference 7

Exhibit 9. COMPOSITIONS OF SOLID FEEDSTOCKS

Feedstock	Pittsburgh Seam Coal	Fairmont Steam Coal	Coal Tar	Fluid Coker Petroleum Coke	Kentucky No. 9 Coal	Itsudan Coal (Japan)
Ultimate Analysis, Weight %						
Carbon	75.1	75.1	88.1	88.2	70.5	64.3
Hydrogen	5.1	5.0	5.7	2.0	4.9	4.9
Nitrogen	1.4	1.5	0.9	2.2	1.5	0.9
Sulfur	1.5	2.2	0.8	5.3	4.3	1.8
Oxygen	8.0	5.6	4.4	2.0	7.0	15.0
Ash	8.9	10.6	0.1	0.3	11.8	13.1
Gross Heating Value, BTU per lb.	13,200	13,300	15,960	14,723	12,800	11,510

September 6, 1974

SOURCE: Reference 25

Exhibit 10. COMPOSITIONS OF GASES PRODUCED FROM SOLID FEEDSTOCKS

Raw Material	Pittsburgh Seam Coal	Pittsburgh Seam Coal	Fairmont Steam Coal	Coal Tar	Fluid Coker Petroleum Coke	Kentucky No. 9 Coal	Itsudan Coal
Oxidant	oxygen	air	air	oxygen	oxygen	oxygen	oxygen
Fuel Feed System	steam-slurry	steam-slurry	steam-slurry	molten tar	steam-slurry	water slurry pre-heated	steam-slurry skimmed
Product Gas Analysis, mol %							
Carbon Monoxide	41.1	14.4	13.7	54.3	54.0	39.8	45.8
Hydrogen	42.1	15.3	15.8	38.9	30.2	39.3	39.6
Carbon Dioxide	16.0	11.0	11.4	5.7	14.0	19.8	12.9
Methane	0.2	0.2	0.5	0.1	0.1	0.3	0.8
Argon	-	0.6	-	-	-	0.1	0.1
Nitrogen	0.4	58.4	58.5	0.8	0.5	0.3	0.3
Hydrogen Sulfide	0.2	0.1	0.1	0.2	1.1	0.3	0.4
Carbonyl Sulfide	0.0	0.0	0.0	0.0	0.1	0.1	0.1

September 6, 1974

SOURCE: Reference 25

Cost data in Exhibits 12 through 14 are from the 1973-1974 time period. If updated costs of equipment, fuel, and labor were used, current costs could be estimated from the relationships that follow:[26]

Design Criteria - The design study was based on a fuel consumption rate of 10,000 barrels per day of heavy residual oil, using representative, rather than the most favorable parameters from present commercial gas turbine state of the art as listed. (Exhibit 11.)

Capital Costs for Various Types of Electric Power Plants - The capital costs of the various types of power plants considered in the study are reliable in a gross sense since there are available cost data. The costs are not precise in that such costs vary considerably with plant location and design specifics. For the Texaco combined-cycle plant, there are cost data for the various plant sections or components even though the plant being studied has not been built. None of the equipment requires new design or development.

Estimated Fuel Costs - Fuel costs were taken from the January 15, 1974 Platt's Oilgram. While such costs have changed and are changing rapidly, price differentials, between distillate and low sulfur fuels on one hand and high sulfur residua on the other, are likely to remain. This chart also gives calculated system performance for the previously stated design criteria. The Texaco combined-cycle plant gives very respectable performance with higher pressure ratio, higher turbine inlet temperature and higher compression and turbine efficiencies presently available in some units. Steam plants have been built with thermal efficiencies of 40+ percent, but such plants are high cost, relatively inflexible, and generally not favored by the utility industry. The fuel costs per KWH for the various types of plants and for the fuels and prices listed are given at the bottom of the chart. (Exhibit 12.)

Estimated Savings Using Texaco System - The estimated savings listed (in Exhibit 13) are for fuel charges alone, based on the fuel costs per kwh of the previous chart (Exhibit 12). These savings leave substantial cushion to absorb the higher capital investment and for differences in operating expenses of the Texaco system as compared to the alternate systems requiring low sulfur fuels.

Cost of Producing Electricity - The final chart (Exhibit 14) estimates the cost of producing electricity by the Texaco combined-cycle system. This estimate was made some time ago and is based on a fuel cost of only $3.00 per barrel. However,

Exhibit 11. DESIGN CRITERIA: GASIFICATION, PURIFICATION AND COMBINED CYCLE POWER PLANT

Inlet Air Temperature, °F	60
Pressure, psia	14.696
Syngas Generation	
Oil feed rate, bbl/day	10000
type	900°F + Arabian Heavy Resid.
Waste Heat Boiler	
Steam Pressure, psia	1300
Gas Turbine	
Compressor, Pressure Ratio	12
Efficiency, %	84
Turbine Inlet Temperature, °F	1950
Efficiency, %	86
Exhaust Pressure, inches H_2O	10
Waste Heat Boiler	
Steam Pressure, psia	1300
Superheat Temperature, °F	908
Stack Gas Temperature, °F	300
Power Steam Turbine	
Efficiency, %	85
Exhaust pressure, psia	2
Alternator Efficiency, %	98.2

SOURCE: Reference 26

Exhibit 12. ESTIMATED FUEL COSTS FOR SELECTED TYPES OF ELECTRIC POWER PLANTS

Fuel Oil	Turbine Fuel (# 2 Heating Oil)	Low-Sulfur #6 Fuel Oil		#6 Fuel Oil
% Sulfur	0.2	0.3	0.5	2.8
Higher Heating Value MM BTU/BBL.	5.880	6.000	6.000	6.300
Price				
$/BBL.	23.10	12.57	12.21	9.20
$/MM BTU	3.929	2.095	2.035	1.460
Plant	Combined Cycle	Oil-Fired Steam Boilers		Texaco
Heat Rate, BTU/KW hr.	8500	9225	9225	8900
Thermal Efficiency	40.2	37.0	37.0	38.4
Fuel Cost, Mil/KW hr.	33.40	19.33	18.77	12.99

SOURCE: Reference 26

Exhibit 13. ESTIMATED SAVINGS USING TEXACO SYSTEM @ 12.99 M/KWH

	VS. #2 in Combined Cycle	VS. #6 in Conventional Steam	
@ M/KWH	33.40	19.33	18.77
Savings per KWH	20.41	6.34	5.78
Savings Per hour on 294.4 M/W	$6009.	$1866.	$1702.
Savings Per year @8000 hrs.	$48,069,632.	$14,931,968.	$13,613,056.
Savings Per year @6000 hrs.	$36,052,224.	$11,198,976.	$10,209,792.

SOURCE: Reference 26

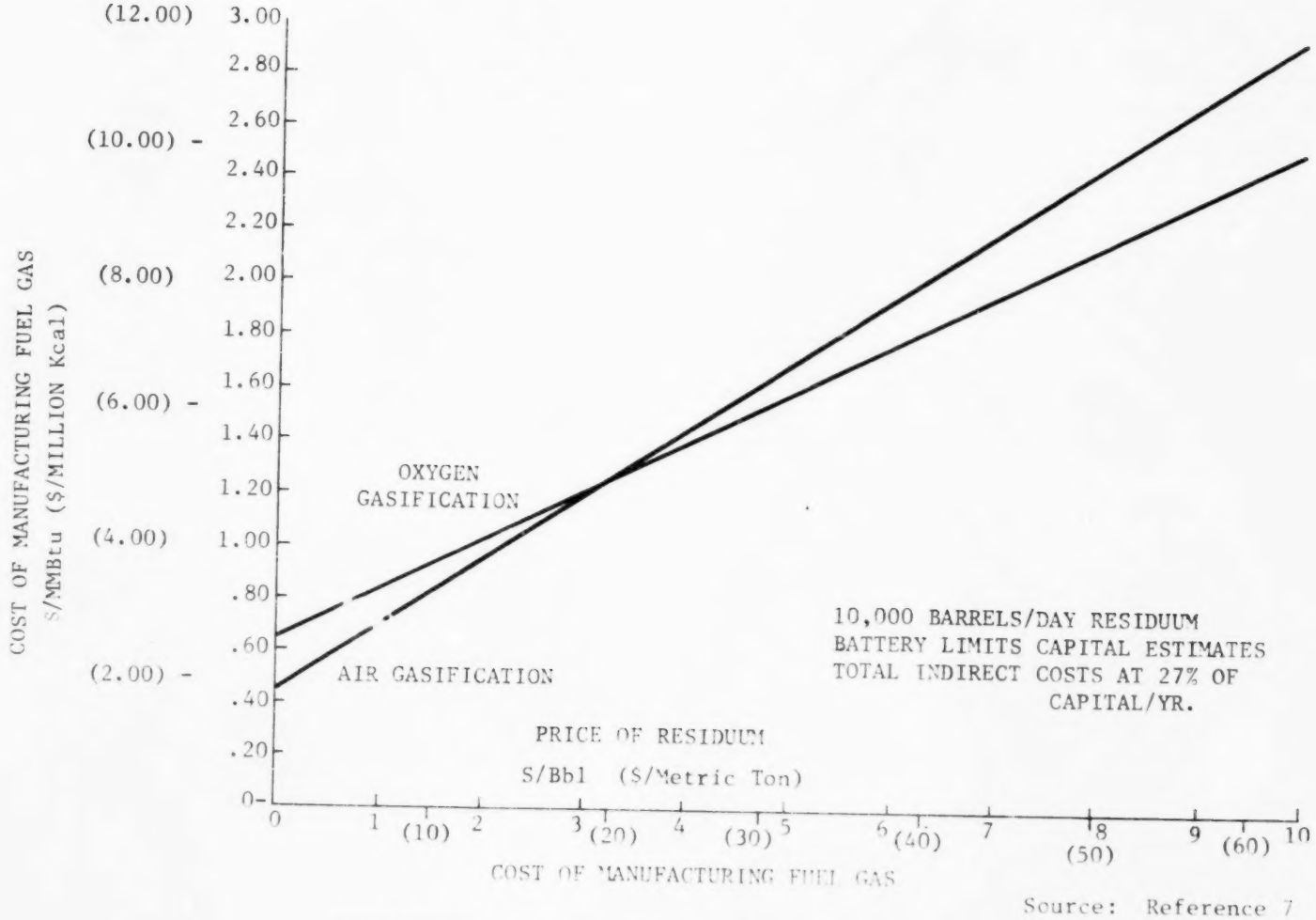
Exhibit 14. COST OF PRODUCING ELECTRICITY

Output, MW				294.4	
Total investment, $MM				70.5	
On stream, hr./yr.				6000	8000
	Requirement	*Unit Price*		*Mil/KW hr.*	
Fuel					
Residual Oil	10000 bbl./day	$3.00 bbl.		4.25	4.25
Utilities					
Circ.CW	130000 gal./min.	$0.02/M gal.		0.53	0.53
Raw Water	125 gal./min.	$0.10/M gal.		0.01	0.01
Chemicals	100 $/day			0.01	0.01
		Sub Total		0.55	0.55
Direct Operations, Costs			$/yr.		
Direct Operating Labor, 10 opr./shift, $12000/yr.			480000	0.27	0.20
Supervision, 10% of operating labor			48000	0.03	0.02
Maintenance, 3% of total investment/yr.			2115000	1.20	0.90
Maintenance supplies, 15% of Maintenance			317000	0.18	0.14
		Sub Total	2960000	1.68	1.26
Indirect Operating Costs					
Payroll overhead, 10% of opr. + Supv.			52800	0.03	0.02
General overhead, 50% of total direct opg.			1480000	0.84	0.63
Ins. + Taxes, 2.5% of total investment			1763000	1.00	0.75
Depreciation, 6.67% of total investment			4700000	2.66	2.00
		Sub Total	7996000	4.53	3.40
		TOTAL PRODUCTION COST		11.01	9.46

SOURCE: Reference 26

the unit requirements of raw materials, utilities, operating labor and indirect operating costs are indicated in sufficient detail so that current local unit prices could be assigned to fuel oil, the utilities and the direct and indirect operating costs to produce a revised cost estimate which would be appropriate for your particular circumstances.

Another cost relationship of interest appears in Exhibit 15. This shows the effect of fuel prices (in this case, residual oil) on the cost of producing clean fuel gas using air or oxygen as the oxidant.[7]



Source: Reference 7

EXHIBIT 15. CLEAN FUEL GAS MANUFACTURE - ECONOMICS